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PARAMETER WIGGLER FREE ELECTRON LASER

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# MICROWAVE AMPLIFICATION USING A VARIABLE PARAMETER WIGGLER FREE ELECTRON LASER

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The Free Electron Laser (FEL) produces coherent radiation by extracting energy from an electron beam, just as in conventional microwave devices. The means of converting the energy from kinetic to electromagnetic is via the fast wave interaction<sup>1</sup>; no slow wave structure is required to reduce the phase velocity of the electromagnetic wave. The electron beam is bunched in a ponderomotive well created by the electromagnetic wave and an externally applied transverse periodic magnetic field.<sup>2</sup> The frequency is determined by a double Doppler shift of the spatial period of the applied wiggler magnetic field. The wavelength of the emitted radiation is

$$\lambda_s = \frac{\lambda_w}{2\gamma^2} \left( 1 + \frac{1}{2} \left( \frac{eB_w \lambda_w}{2\pi m_0 c^2} \right)^2 \right)$$

where  $\lambda_w$  is the length of the wiggler period,  $B_w$  is the peak wiggler field strength, and  $\gamma$  is the total energy of the electron in units of electron rest mass ( $\gamma = 1 + eV/mc^2$ ). Due to the  $\gamma^2$  scaling, laboratory scale structures (magnetic wigglers) can produce quite short wavelength radiation.

We have operated such a device in the millimeter wave regime. The experimental configuration is shown in Fig. 1. The electron beam used in the experiment is generated by an induction linac. The 3.3 MeV beam ( $\gamma = 7.5$ ) has a peak current of 6 kA and a pulse length of 25 ns. The accelerator operates at a 1 Hz repetition rate. Both the current and the emittance of the beam are too high for efficient FEL operation; therefore, an emittance filter is used to reduce the current to 500A and the emittance from 1.5 pi radian-cm to 0.47 pi radian-cm (normalized).

The wiggler is 3 meters long and consists of two series of alternately opposing solenoids. The cusp fields from these solenoids provide a spatially alternating, linearly polarized, magnetic field. The pulsed wiggler can provide a peak field on axis of 5 kG and has a spatial period of 9.8 cm. Each two periods of the

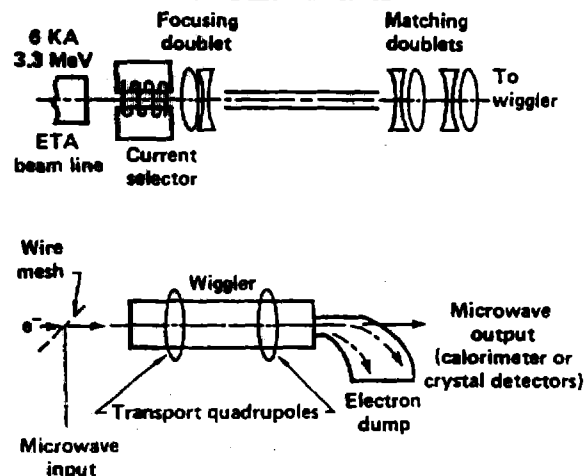


Figure 1. Schematic of FEL experiment.

wiggler is driven by its own power supply; we are thus able to vary the length or profile of the wiggler field along the interaction region. Vertical focusing of the electron beam is provided by the natural focusing of the wiggler field, while quadrupoles are used to focus the beam in the horizontal direction. The interaction region is a 2.9 cm by 9.8 cm stainless-steel waveguide. The TE<sub>01</sub> mode is driven in the FEL interaction.

A special probe was used to provide real-time imaging of the beam in the interaction region. The metallic face of this probe also served as a reflector for any microwaves generated in the interaction region. These reflected microwaves were monitored by a crystal detector located at the position where the input signal for the amplifier would normally be launched. By extracting the probe we are continuously lengthening the interaction region. We thus found the microwave signal to grow from noise at a rate of 13.4 dB/m for a beam current of 400A in the wiggler.

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We have studied the gain of the amplifier as a function of both wiggler field intensity and wiggler length. The output of the amplifier is shown in Fig. 2, as a function of wiggler field intensity for a 1-, 2-, and 3-meter-long wiggler. In all of these cases the injected signal power was 30 kW. The peak power of 80 MW is achieved by 2 meters; this is near the point at which the amplifier has saturated. Detailed study of the gain versus length for a fixed magnetic field shows that the emitted power exhibits an oscillatory structure beyond saturation indicative of the electron beam first giving energy to the radiation, then extracting energy from the radiation. The linear gain up to saturation is roughly 17 dB/m (for 450A of beam current in the wiggler), which is close to the small signal gain measured in the method described above.

The experiment was modeled with a two-dimensional numerical simulation. The simulation follows 4096 electrons in a single ponderomotive potential well as they undergo betatron oscillations in the transverse dimension, while obeying the longitudinal equations of motion derived by Kroll, Morton and Rosenbluth.<sup>3</sup> These longitudinal equations in the simulation use local values of the fields so that off-axis effects are fully included and take into account the effects of betatron motion on the parallel electron velocity. The electrons provide the source for the electromagnetic field through the wave equation derived by Colson.<sup>4</sup> This description has been generalized to include the transverse variation of the electric field in the waveguide (TE<sub>n1</sub> modes, for n even are followed). Figure 2 includes some of the results of the simulation which agree very well with the experimental results. Only one key experimental parameter is unknown, that being the extent to which the electrons are mismatched to their equilibrium orbit in the wiggler. Using a maximum radial excursion of 0.8 cm, we have been able to fit all of the experimental results. Due to our ability to predict the behavior of the experiment (including the detailed structure as that in Fig. 2), we feel the experiment is well understood.

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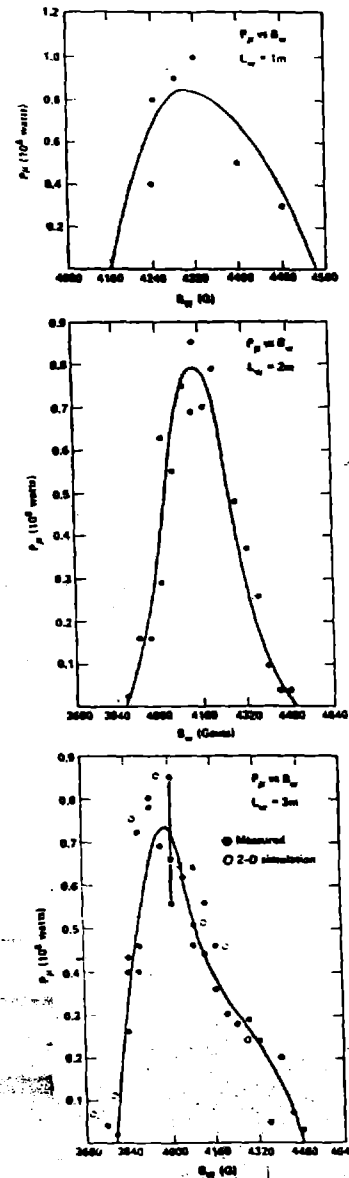


Figure 2. Amplifier gain for 3 wiggler lengths.